PARACHUTE BASED DECELERATION SYSTEM

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Introduction

On completion of the designated mission - orbiting or interplanetary, Crew Module of Human Spaceflight Missions has to safely reach back to a pre-determined destination on earth for recovery of crew and systems. This maneuver is executed in measured steps which involves a de-boost from orbit and a controlled re-entry often using aero braking generated by the Crew Module configuration. In most of the human spaceflight missions, the final phase is always a slow descent using parachute. However, prior to that, there will be a series of parachutes in action. The design, development and flight demonstration of parachute based deceleration system is an involved task with a number of design iterations and a lot of performance demonstration tests.

Re-entry bodies usually travel at hypersonic velocities and the initial deceleration is quite often achieved through aero-braking. However terminal velocity of the module after aerobraking is still very high and does not permit a safe landing. Hence, further deceleration of the module has to be achieved through inbuilt systems viz., retro rockets or a parachute based deceleration system. Parachute based deceleration systems are widely preferred for re-entry missions involving crew/payload recovery, considering its simplicity and hence, improved reliability, higher achievable deceleration levels with lesser overall mass, use of toxic free materials etc. Parachutes being made of fabric materials are easy to be packed within a small volume. Parachutes design is mission specific and depends on payload mass and terminal velocity requirement. For re-entry missions attempting sea landing such as proposed Indian Human Spaceflight Mission, terminal velocity requirement can be achieved with parachutes having less drag area, compared to land-landing mission.

For re-entry missions involving human, there must be a mandatory transition from mission critical to safety critical design. Human spaceflight mission demand safety critical certification which requires more stringent control of all the systems. Accordingly, the parachute systems used in human spaceflight missions require human rating and reliability aspects including, performance in the limits of operational and design values have to be comprehensively validated before attempting actual human spaceflight.

The prowess of India in the realm of space science and technology has been proven through an array of success in the past three decades. This includes the string of achievements made in launch vehicle area, satellite area, and interplanetary missions like Chandrayaan and Mars Orbiter Missions. The last decade has also witnessed ISRO's capability to launch 4 ton class of payloads to GTO, using indigenously developed GSLV Mk III. Manned spaceflight missions are considered as the next logical step to embark upon, and activities towards this was seeded in 2004. The success of Space Capsule Recovery Experiment (SRE) in 2007, the Crew Module Atmospheric Re-entry Experiment (CARE) in 2014, and the Pad Abort Test (PAT) flight in 2018 paved the way for ISRO in taking up a leap towards having a manned flight in the near future and hence, entering into the elite club of countries having capability of conducting manned spaceflights.

Parachute System for Indian Re-entry Missions - A Prelude

Safe landing and recovery of re-entry payloads was first successfully demonstrated by ISRO through Space Capsule Recovery Experiment (SRE) mission in 2007. SRE capsule, with a mass of 500 kg, had a sphere cone flare configuration with parachute system consisting of Ø1 m flat square pilot parachute, Ø 3 m ribbon canopy drogue parachute, and Ø12.6 m aero conical main parachute. After de-boost, re-entry, and aero braking, the module had a velocity of 115 m/s at 5 km altitude. A drogue gun was actuated at 5 km altitude to deploy the pilot parachute. The pilot parachute pulled out a lid plate which is connected to the drogue parachute. The drogue parachute was thus

extracted and deployed which brought down the velocity of the capsule from 115 m/s to ~ 50 m/s. At 2 km altitude, the drogue parachute was released which in turn pulled out and deployed the main parachute. The deployed main parachute brought down the velocity of the capsule from 50 m/s to the final terminal velocity of 12 m/s. Upon touch down, the main parachute got disconnected and a floatation system was deployed to keep the capsule afloat. The SRE parachute system was validated using a number of tests including wind tunnel tests to estimate the drag coefficient of parachutes, Aircraft drop trials with dummy mass, Rail Track Rocket Sled Test (RTRS), and integrated drop test using helicopter to simulate the entire parachute chain.

With the confidence gained and lessons learned from SRE programme, attempts were initiated to configure parachute systems for 3 t class re-entry payloads, as a forerunner to parachute systems for manned spaceflight. The payload considered was of blunt sphere cone configuration with external aerodynamic shape simulating Indian Crew Module. The parachute system is accommodated at the apex region of module. The parachutes are housed inside an apex cover which is separated prior to parachute system initiation. Based on detailed analysis, a two stage deceleration system was found to be suitable. The first stage will stabilize the payload (hereafter called Crew Module) and decelerate it to safe deployment conditions for second stage initiation. The deployment of first stage was planned at 7 km altitude where the velocity of Crew Module is around 155 m/s. First stage parachute system decelerates the Crew Module to ~70 m/s terminal velocity. Thereafter, the second stage parachute system is initiated at 3 km altitude, reducing the module velocity to its terminal value of ~8 m/s for safe landing in sea.

Development of Parachute System for Indian Crew Module

In this developmental effort, the objective was to design, develop, qualify, and flight test a reliable parachute based deceleration system for 3 t class payload system. The payload was Indian Crew Module with mass specified as 3300 ±100 kg. The module had a diameter of 3.1 m, length of 2.6 m, and semi-cone angle of 14°. The initiation altitude considered was from 1.5 - 7 km, considering abort scenarios. The velocity at the time of initiation was from 60 to 180 m/s. The peak deceleration during parachute functioning had to be restricted to < 6g considering crew tolerance limits. Considering manned mission requirements, adequate redundancy and fault tolerance needs to be provided in the system. Also, the system had to be packed and accommodated in the given constrained volume at the apex region of Crew Module. Requirement also demands the system to have same terminal velocity during nominal and abort conditions.

Wide literature survey was carried out before proposing system concepts for Indian Crew Module deceleration system. Lessons learned from Apollo, Soyuz, and Orion parachute systems kindled the thought process towards arriving at an optimum configuration [1]. It was understood that a cluster parachute system makes the module more stable against oscillations. Also, redundancy in stages, avoids use of failure detection and back-up parachute systems. Based on standards practiced in parachute system design, it is decided that a safety factor of 2 is applicable for critical elements and 1.6 for non critical elements. Seam efficiency, abrasion loss, environmental loss, fatigue loss, and line conversion factors were considered in extra, which gave a design factor of 2.76 for critical components and 2.21 for other components.

Based on requirements and standards, a preliminary conceptual configuration was evolved with two stage deceleration system. The configuration was basically a variant of SRE parachute system, with clustered parachutes for better stability and redundancy. The initial scheme had three types of parachutes with the apex cover being extracted by two smaller parachutes. The separated apex cover pulls out the two first stage parachutes called the drogue parachutes. The drogue parachutes, after rendering the initial deceleration, separates and deploys the main parachutes in-line. The main parachutes bring the module to its terminal velocity and gets separated upon touch down. Detailed studies revealed that extracting drogue parachute using apex cover brings the Crew Module in line with the apex cover, increasing chances of re-contact. Hence it was decided to use separate pilot parachutes for deployment of drogue parachutes. Hence the two chain deceleration system was finalised with

- Two Apex Cover Separation (ACS) parachutes for extracting the apex cover
- Two pilot parachutes for extracting and deploying the drogue parachutes
- Two drogue parachutes as first stage decelerator
- Two main parachutes as second stage decelerator

Design of the three types of parachutes were finalised based on the demanded use. Apex Cover Separation (ACS) parachutes and pilot parachutes were designed considering quick, reliable deployment and good stability characteristics. ACS parachutes, in addition, has to prevent apex cover from re-contacting the Crew Module. pilot parachutes should have better drag coefficient to pullout the drogue parachute pack. The drogue parachutes should have high drag coefficients and should be capable of operating in a wide range of dynamic pressure for longer durations. It should be capable of reducing the velocity towards providing favourable deployment conditions for main parachute. It should also provide quick stabilization to Crew Module after ejection of apex cover and pilot parachute. Main parachutes should have quick opening capability with low opening shock factor and high drag coefficient.

Detailed specification of the payload system where then laid down which is essential for design of parachute system. The design was carried out for:

- Mass of CM (without Apex cover) : $3430 \pm 15\%$ kg
- Mass of apex cover : 204 + 2 kg (realised mass)
- cd of CM : $0.626 \pm 10\%$ @ Mach 0.5 (Reference area 7.54 m^2 and angle of attack 20°)
- Dispersion of parachute Cd : $\pm 10\%$
- Oscillations of parachute : $\pm 15°$ (Half cone angle)
- Initiation altitude : 15.3 km
- Dynamic pressure at deployment : 6.9 kPa (max)
- Touchdown velocity : ≤ 12 m/s with single Main parachutes

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- Deceleration @ parachute opening : ≤ 6 g
- Maximum pitch/yaw rate of CM : 40 deg/sec

Pad abort condition

- Initiation altitude : 1.5 Km
- Velocity of deployment : 75 - 115 m/s (min)

Configuration options were worked out based on detailed design and analysis considering input specifications and terminal velocity requirements. Pilot and ACS parachutes were same in all configurations.

The first configuration (configuration 1) was with single parachute in each stage. It had two Ø 2.5 ACS parachutes (one redundant) for apex cover separation. Single Ø 5 m drogue, and Ø 38 m main parachute was provided in each chain of the two chain system, one being back-up redundant system. The back-up comes into picture only in case of primary chain failure. The back-up system is initiated using a Ø 2.5 m pilot parachute.

The second configuration (Configuration 2) had two Ø 2.5 m ACS parachutes for apex cover separation and two Ø 2.5 m pilot parachutes for simultaneous and independent extraction of two Ø 5 m drogue parachutes. After first stage deceleration, the drogue parachutes are released and three Ø 27.4 m main parachutes are independently extracted and deployed by three Ø 2.5 m pilot parachutes.

The third and recommended configuration (Configuration 3) was with two Ø 2.5 m ACS parachutes extracting the apex cover, two Ø 2.5 m pilot parachutes extracting and deploying the Ø 6.3 m drogue parachutes, and two Ø 31m main parachutes extracted and deployed using drogue parachutes.

The configuration options are shown in Fig.1.

In order to reduce the opening loads during deployment, the main parachute is provided with single stage reefing. Mid gore reefing was adopted with reefing rings attached to the skirt of the parachute in the centre of each gore. This renders uniform inflation process and reefed drag area. The system initially had a confluence for the main parachute at the attachment location. Sequential

straps were used to connect the main parachutes to the Crew Module. Later-on, the confluence point was removed and the main parachutes were independently attached to the Crew Module. Hence the system became dual redundant with independent extraction of each chain. Final recommended configuration is shown in Fig.2.

Parachutes were selected considering porosity, stability characteristics, and drag coefficient. Drag coefficient for the parachutes were adopted from design standards and were validated using extensive wind tunnel test programme. Details of parachutes used in CM deceleration system is given in Table-1.

Material for parachute fabrication were selected based on mass and packing volume requirements, without compromising on strength. Nylon material is used for canopy ribbon, canopy fabric, and deployment bags. Considering high strength to weight ratio, Kevlar is used for risers, suspension lines, and reinforcement tapes. Cotton week ties are also used for stowing and packing the parachutes.

The parachute design also proliferated design and development of a host of pyro devices like Mortar for controlled ejection of smaller parachutes with required ejection velocity, pyro thrusters for ejection and jettisoning of apex cover with specified velocity, Parachute Releaser units (PRU) for release of parachutes after functioning, and Reefing Line Cutter for dis-reefing of main parachutes. ACS and pilot parachutes were proposed to be deployed using Mortar at an ejection velocity of 43 ± 3 m/s. Pyro thrusters were used to separate and jettison the apex cover at a velocity of 8 to 10 m/s, before getting extracted using ACS parachutes. Parachute releasers were used to release the parachute at the end of functioning regime. Pin puller type PRU with main charge redundancy was employed in Crew Module deceleration system. Design and development of RLC was the most challenging among all which went through many design iterations. The function of RLC is to cut the reefing line in the main parachute after the specified delay of 7 ± 1 s. The main parachutes will be initially inflated in reefed condition. The restriction from full inflation is provided by means of a reefing line which is cut after specified delay time to achieve full inflation. The RLC has got a triggering mechanism which is actuated at the end of main parachute stretch. The triggering mechanism consists of a striker which fires a percussion initiator. The percussion initiator fires a delay charge which burns with the specified delay (7 ± 1 s) to initiate a pyro cutter which cuts the reefing line. Each parachute is provided with two RLCs for redundancy.

Table-1 : Parachutes in CM deceleration system

	ACS	**Pilot**	**Drogue**	**Main**
Number of parachutes	2	2	2	2
Nominal diameter	2.5 m	2.5 m	6.3 m	31 m
Type of parachute	Ring slot	Ring slot	Conical ribbon	Flat circular slotted
Mass	2.2. kg	2.2. kg	18 kg	79 kg
Nominal drag coefficient	0.56 ± 10%	0.56 ± 10%	0.5 ± 10%	0.75 ± 10%
Initiation altitude	15.3 km	15.3 km	14.7 km	5 km
Initiation velocity	226 m/s	226 m/s	214 m/s	52 m/s
Stretching time	0.47 ± 10% s	0.39 ± 10% s	0.26 ± 10% s	1.6 ± 10 s
Inflation time	0.15 ± 10% s	0.15 ± 10% s	0.40 ± 10% s	1.2 ± 10% s (Reefed)
Reefing delay	-	-	-	7 ± 1 s
Dis-reefing time	-	-	-	1.7 ± 10% s
Included air mass	0.32 kg	0.32 kg	5 kg	2300 kg
Termination altitude	-	-	5 km	MSL
Termination velocity	-	-	52 m/s	7.4 m/s (Cluster) 10.1 m/s (Single)

The deceleration system chain is initiated after separation of the apex cover using Mortar deployed ACS parachutes. The pilot parachutes are then deployed using Mortar which independently extracts two drogue parachutes. The drogue parachute after providing initial deceleration further independently extracts the two main parachutes through extraction bridles. The main parachutes decelerate the module to final touchdown velocity. In order to reduce opening loads on main parachute, it is inflated in two stages with reefing system. Layout of parachute system inside parachute compartment is shown in Fig.3.

The main parachute consists of 84 rigging lines which confluence at a single point. From the confluence point, the rigging lines are connected to the riser using a metallic filling called Rigging Line Adaptor. The adaptor provides interface for 84 rigging lines on one side and the main parachute riser on the other. The risers of drogue and main parachutes are connected to the Crew Module structure through a Parachute Releaser Adaptor (PRA). The PRAs interfaced to Parachute Release Units which are mounted on to two bridging members in the parachute compartment. Drogue parachute is mounted inside a metallic container with provision for interfacing the retention system.

Qualification systems and associated auxiliaries went through extensive qualification programme before getting inducted into flight. The canopy fabric, rigging lines, tapes, riser, weak ties, and pack cover were structurally qualified through sample testing. The fabric materials were also subjected to structural testing at cryogenic temperature to estimate extend of strength degradation. All the metallic components in the system were structurally qualified using UTM tests. Functional qualification of all the elements were carried out through Air drop tests and RTRS tests.

Pyro devices in the system have gone through extensive development and qualification tests prior to flight tests. All hardware items were structurally qualified to the required levels. The Mortar systems have initially undergone ground ejection test with dummy mass followed by tests with ACS/Pilot parachutes. The Mortar charge quantity was finalised based on several ground trials. This was followed by qualification trials and batch acceptance tests, including environmental tests. Pyro-thruster and Parachute Release Units also have undergone similar test cycle. Qualification of Reefing Line Cutter was a major challenge since the design had undergone several design changes based on test observations. More than hundreds of trials were carried out for qualifying the delay column and percussion primer. The triggering unit, delay column, and cutter unit were separately tested prior to integrated tests. The device had undergone high-g testing and dynamic load testing under various orientation conditions, apart from the standard batch acceptance tests. The design of the device was modified based on observations in parachute air-drop tests, which are listed in subsequent section.

RTRS Tests: The smaller size parachutes viz. ACS and Drogue parachutes were structurally and functionally qualified using Rail Track Rocket Sled Tests which were conducted in five phases. In these tests, the parachute systems were mounted on top of a sled which was accelerated using solid rocket motors. The parachutes were deployed at the required velocity and parameters were captured using data acquisition systems. The parachutes underwent structural modifications and additional strengthening based on RTRS test results. The drogue parachute was further qualified through aerial drop tests using aircraft, to verify the packing scheme.

Aircraft Drop Tests: The main parachutes were qualified through aerial drop tests using aircrafts. Prior to the tests, the extraction scheme was validated using bench trials. Initial tests were done with payload mass ranging from 240 to 3000 kg using aircraft. The tests were aimed towards validating the packing scheme and its subsequent modifications, instrumentation scheme, and to have a preliminary idea on opening load profile. About ten tests were conducted using aircraft, one in cluster parachute configuration. These tests provided valuable data towards modifying the parachute stowing and packing scheme. Tests with higher payloads, simulating flight qualification loads, were carried out using a bigger aircraft. These tests were conducted using payload mass ranging from 4000-5000 kg. The main parachute were subjected to flight qualification levels in these tests. The initial test with this aircraft had parachute with reefing line made of nylon cord. The RLC and reefing scheme was validated using an smaller aircraft drop test earlier. However, the RLCs failed to function as the actuation pins were not pulled out. Moreover, severe bending was seen in the actuation pins of both RLCs. Subsequently, the design of RLC was modified for fail free operation from any pull angle. Additional strengthening was given to RLC, including material change. The reefing system was modified by changing the reefing line from Nylon cord to Nylon tape and the ends were stitched instead of knotting. RLC was kept in a

pouch made of thick Nylon cloth with foam padding on top and bottom. Despite of all these, the test resulted in a failure as the canopy of main parachute got snatched off during deployment. The phenomenon and effect of snatch force was clearly understood in the test which lead to the modification of Reefing Line Cutter to the current final configuration. The RLC, weighing about 1 kg, rendered heavy snatch force at the end of parachute stretching due to reversal in relative velocity direction. The design of RLC was subsequently modified and the mass was reduced to ~390 g. The modified scheme was further tested using smaller and big aircrafts before induction in flight. Summary of drop tests conducted is shown in Table-2.

Integrated Air Drop Test: Functioning of entire deceleration system chain was successfully validated using a full scale Integrated Air Drop Test (IADT) test. In this test, a shape simulated Crew Module was dropped from an altitude of ~3.75 km using a helicopter. During descent of the module, the entire deceleration sequence, starting from apex cover separation was tested. An additional stabilizer parachute was used in this test to stabilize the module, after release from helicopter. The system went through the entire sequence based on pre-programmed time based command through a sequencer. After dis-reefing of main parachute, a terminal velocity of ~6m/s was achieved. The module after touchdown was subsequently recovered. The velocity profile has got good matching with prediction and is shown in Fig.4.

Table-2 : Aerial airdrop tests of main parachute

Test No.	Payload (kg)	Velocity (km/h)	Altitude (m)	Status	Remarks
1	3000	240	500	Success	Reefed peak load : 4606 kgf Dis-reefed peak load : 4550 kgf Snatch force : 3906 kgf
2	3000	240	500	Success	Main parachute in cluster configuration Reefed peak : 3421 kgf, Reefed peak : 2563 kgf Dis-reefed peak load : 3102 kgf, Dis-reefed peak : 2562 kgf Snatch force : 3511 kgf, Snatch force : 3234 kgf
3	3000	240	500	Success	Reefed peak load : 4150 kgf Dis-reefed peak load : 4849 kgf
4	500	240	400	Success	Reefed peak load : 708.4 kgf Dis-reefed peak load : 1577 kgf Snatch force : 1336 kgf
5	500	240	500	Failure	The canopy and rigging lines came out together and resulted in entanglement and high snatch load. the pack cover and packing procedure was modified.
6	500	240	500	Success	Test for the main parachute pack cover
7	240	240	500	Success	Test for the modified main parachute pack cover
8	240	240	500	Success	Test for the pyro Reefing Line Cutter

Table-2 : Aerial airdrop tests of main parachute (Contd/-)

Test No.	Payload (kg)	Velocity (km/h)	Altitude (m)	Status	Remarks
9	5000	370	600	Failure	Reefed peak load : 16570 kgf Dis-reefed peak load : 15230 kgf Snatch force : 4702 kgf The reefing line cutters did not function and the reefing line knot got untied
10	5000	370	750	Failure	The parachute failed to deploy. The rigging lines were broken due to the snatch load and parachute collapsed
11	500	240	500	Success	Reefed peak load : 74.3 kN Dis-reefed peak load : 80.26 kN Snatch force : 29.0 kN
12	4200	295	750	Success	Reefed peak load : 166.7 kN Dis-reefed peak load : 152.6 kN Snatch force : 34 kN
13	4000	320	750	Success	Main parachute subjected to 1.07 times of Mission (CARE) Flight load
14	500	240	500	Success	Validated for PAT flight

After successful performance demonstration of deceleration system sequence in IADT, the system was flight proven in the Crew Module Atmospheric Re-entry Experiment (CARE) and Pad Abort Test (PAT) flight.

Crew Module Atmospheric Re-entry Experiment (CARE) [4]

CARE mission was successfully carried out in the maiden flight of GSLV Mk-III, named as LVM3-X / CARE mission. CARE was used as a platform for testing the re-entry technologies envisaged for Crew Module and for validating the performance of parachute based deceleration system. In CARE mission, the Crew Module (which was separated from the launch vehicle at an altitude of 126.5 km), re-entered Earth's atmosphere at about 80 km and descended further in semi-ballistic mode. During the descent from 126.5 km to 80 km, three axis control of the module was ensured using the control system for damping out the rates and to have proper re-entry attitude. Beyond 80 km and after the aero braking phase, further deceleration of the module was achieved using parachute based deceleration system. Based on altitude sensing, the deceleration system chain was initiated at 14.3 km altitude. The apex cover was ejected out and the two Pilot parachutes independently extracted the Drogue parachutes and deployed them. Crew Module decelerated to ~ 50 m/s velocity under the drogue parachute. Subsequently, the drogue parachutes were released and the two main parachutes were fully stretched and deployed. The module descended further under main parachute and made a safe water impact at Bay of Bengal 600 km away from Port Blair. The impact point was less than 5 nautical miles away from the predicted impact point. Crew Module was then recovered by Indian Coast Guard (ICG) and brought back to shore. Confirmation on occurrence of various events during deceleration system functioning was obtained through telemetry, data recorders, axial mode accelera-

tion, bending mode acceleration, strain, shock, and acceleration data from inertial navigation package. Footages from onboard camera also provided data on functioning of deceleration system elements. Data at the time of impact could not be received from telemetry because the module was not in the line of sight of ship based telemetry receiving unit which was located around 100 km from the predicated impact point. Also, the impact data was neither recorded in the onboard data recorder because the impact occurred before the pre-programmed session of recorder. This indicates a relatively higher terminal velocity of the module during touch down. However, the module was found to be structurally intact after recovery.

From onboard camera footages, it was observed that the riser and rigging lines of one of the drogue parachutes came out of the pack cover together as a bunch instead of sequential extraction. The drogue parachute packing scheme was accordingly modified and validated using aerial drop test.

Direct load measurement was not available in CARE and load signatures were translated from strain data. Dis-reefing signatures were not seen in any of the acceleration or strain data. The acceleration in Z direction obtained from CARE flight data against prediction is shown in Fig.5. The predicted curve shows two peaks, one during deployment of the main parachute and the other peak after 7 s indicates dis-reefing. Acceleration under reefed condition was matching with prediction. However, the acceleration peak during dis-reefing is not observed in the flight data.

CARE module velocity values through inertial navigation package were available only up to drogue parachute deployment since reference for the package was lost due to higher rates. Also, the impact happened before the start session of onboard recorder. Velocity estimation was done based on trajectory matching studies up to the point where telemetry data was available. Followed by this, pressure data from the pressure channels were analyzed to determine the altitude and hence the velocity of the module. Available measurements did not give evidence of dis-reefing and an increase was seen in the estimated touchdown velocity estimated using pressure data. The measured data and trajectory matching indicates that the duration of main parachute descent flight is less than the post flight predictions. Based on the observations, robust systems were proposed for terminal velocity measurements in future missions. Data recorders with continuous recording capacity was also proposed to capture all parameters throughout the mission.

Pad Abort Test (PAT) Flight [5]

Performance of Crew Escape System (CES) and its capability to execute a ground based abort was successfully demonstrated through a Pad Abort Test (PAT). By this test, capability to safely eject Crew module from launch pad in case of an exigency was demonstrated. The PAT flight was the first in the series of tests to qualify the Crew Escape System. In Pad Abort Test flight, the test article consisting of the Crew Escape System and Crew Module had a lift-off mass of 12.6 t and overall height of 14 m. Solid Motors in CES are selectively fired depending on the abort condition and for PAT flight they were fired simultaneously. A pitch motor was fired to give a lateral kick to the CES to ensure sufficient range from pad. Within 20 s after lift-off, the Crew Module separated from the CES at an altitude of 2.9 km. The module re-oriented itself by virtue of its aerodynamics. Upon attaining a favourable angle of attack, the parachute sequence was initiated. The apex cover was separated using pyro-thrusters and parachutes. This was followed by Mortar based ejection of pilot parachutes. The pilot parachutes extracted the drogue parachutes which eventually pulled out the main parachutes. The main parachutes, after the specified reefed interval of 7 s, were fully inflated and the module attained its terminal velocity. The sequence of events, being time tagged, was executed as programmed, which resulted in the occurrence of 'window-out' event before the sensing the impact. After splashdown, the module was recovered and brought back for further analysis. The test article including all subsystems was extensively instrumented and the mission was well captured by tracking stations and video.

The flight measurement data has been captured using Telemetry as well as data recorders. Radar altimeter data was used to capture the altitude profile since the navigation started drifting during parachute phase. The events during parachute deployment were time tagged. All the events were executed as planned. Certain modifications were done on parachute systems, based on observations from CARE mission, which included:

- Modified drogue pack cover used for PAT flight: Based on the observation of inadvertent pull out of riser and rigging line from drogue pack cover resulting in a differential delay in deployment of drogue parachutes

in CARE mission. In PAT flight both drogue parachutes were deployed uniformly.

- Abrasion protection sleeves were introduced in drogue parachute riser to prevent likely abrasion of riser with metallic rings in the apex region of Crew Module.

The acceleration profile during Main parachute opening, compared against prediction, is shown in Fig.6.

From the data, it is observed that the parachute systems have functioned satisfactorily in Pad Abort Test flight. Simultaneous ejection and deployment of ACS, pilot, drogue, and main parachutes were confirmed from onboard video. Full inflation of drogue, reefed and dis-reefed inflation of main parachutes are evident from ground and onboard video. Signatures are captured in strain data and acceleration channels. Sequential deployment of both drogue parachutes and main parachutes were confirmed. A relative delay was observed between dis-reefing of two main parachutes. The measured terminal velocity of CM in main parachute (Fig.7) was 7.2 m/s.

Conclusion

Robust design is always warranted for progress in challenging ventures. Parachute systems development for manned spaceflight was a unique endeavor which was attempted for the first time in the country and has rendered promising results. The parachute systems have undergone a successful design and testing cycle through which the system performance was established. Successful flight testing of the system in two demonstration flights gave confidence towards entering into the challenging arena of manned spaceflight. The lessons learned from these tests and missions have laid the foundation for India's aspiration of Gaganyaan in 2021.

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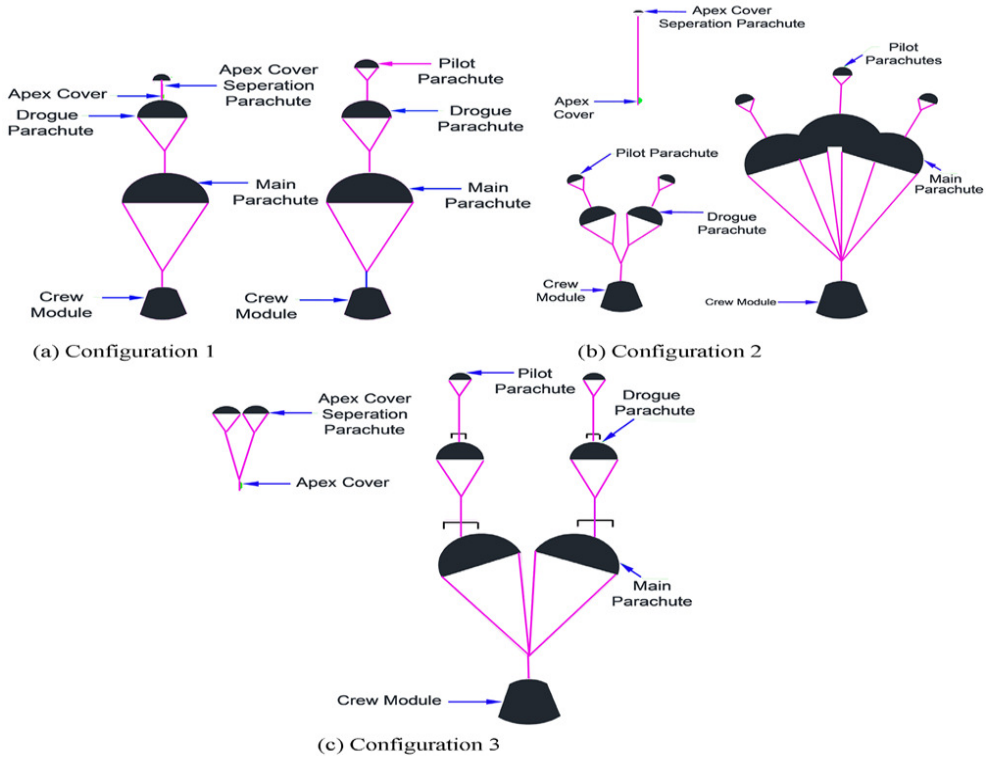

Fig.1 Parachute Configurations

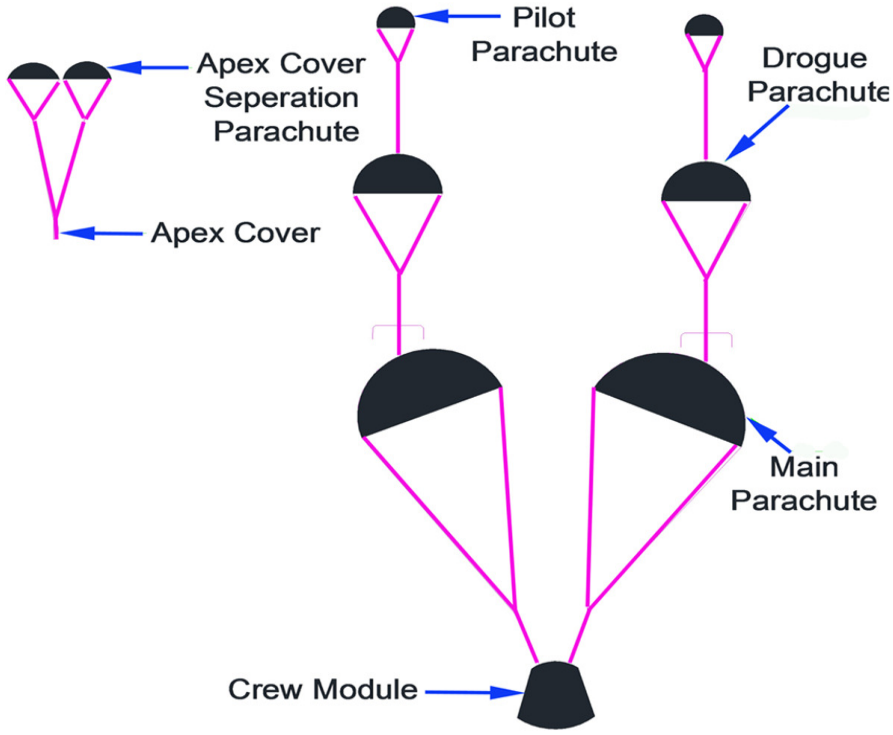

Fig.2 Recommended Configuration for Crew Module Parachute System

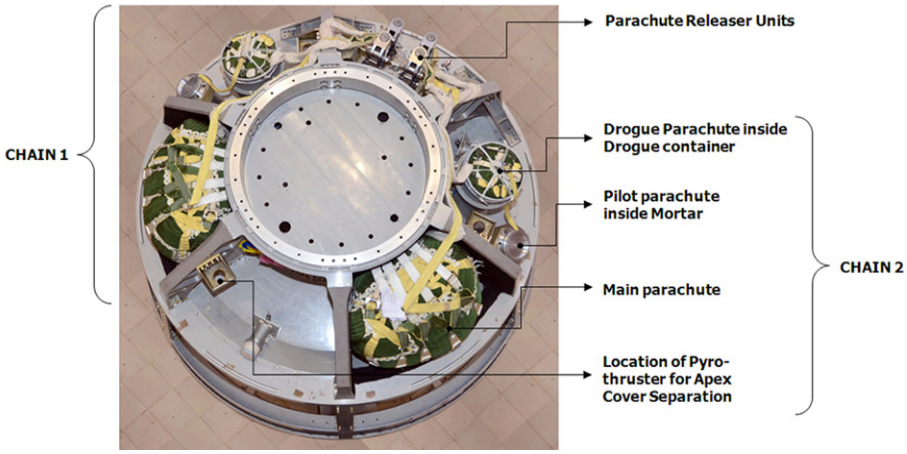

Fig.3 Parachute System Layout Inside Crew Module

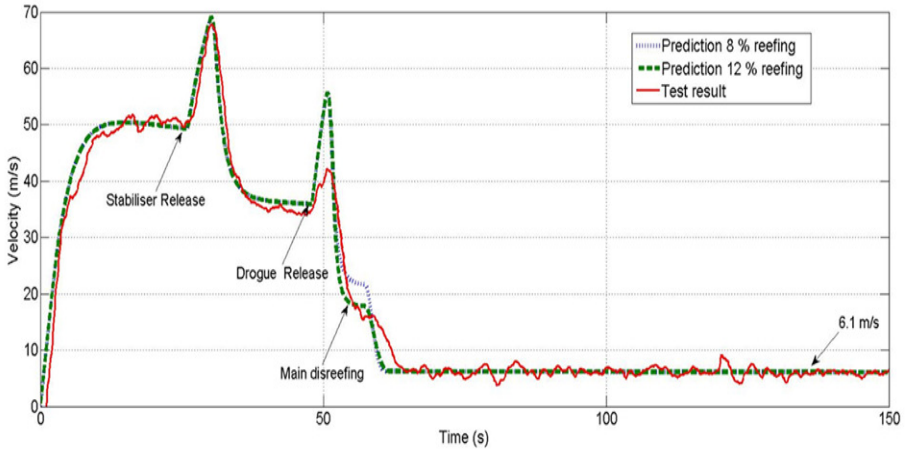

Fig.4 Velocity Profile During IADT

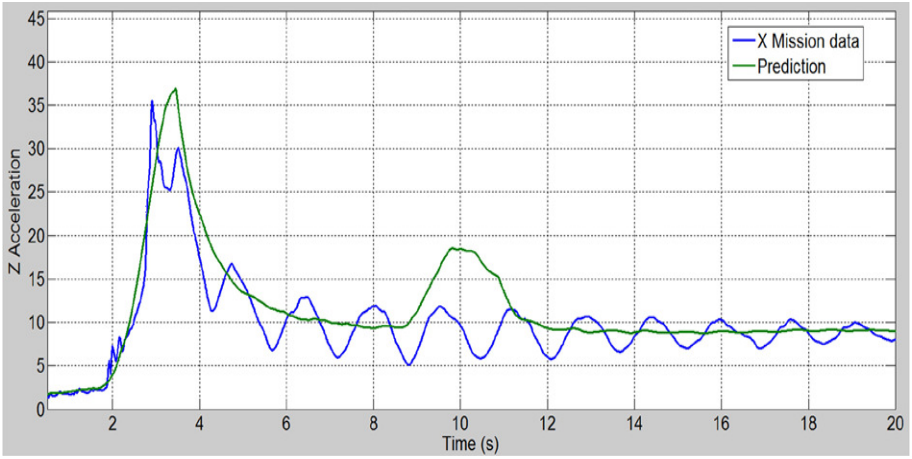

Fig.5 $Z_{Acceleration}$ Vs Time During Main Parachute Phase

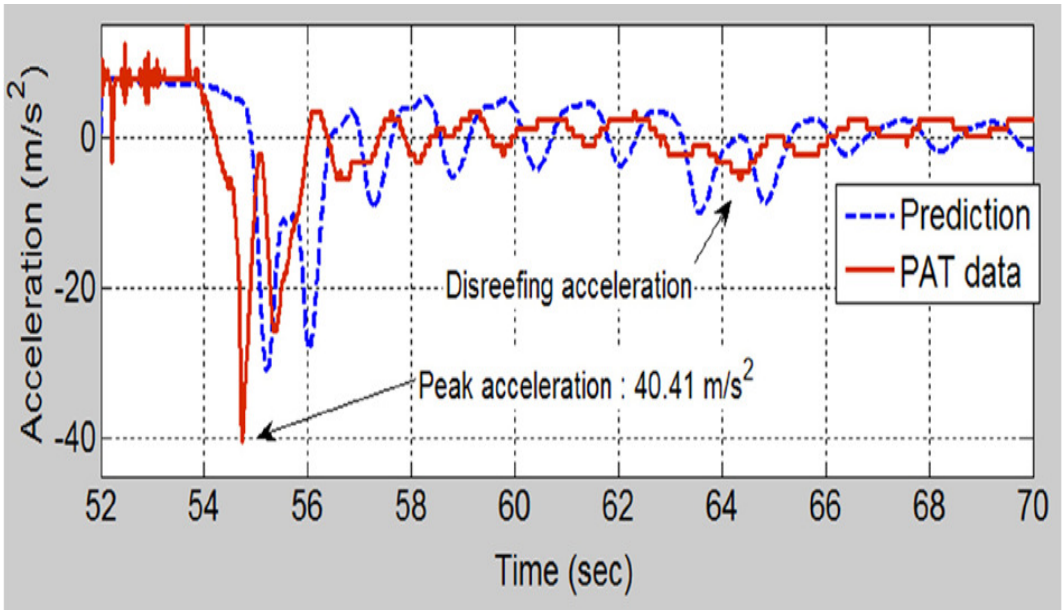

Fig.6 Acceleration Prediction During Main Parachute Opening

Fig.7 Crew Module Descending in Main Parachute (PAT Flight)